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14. ABSTRACT

This paper presents the development of the theoretical basis for the design of sensor networks for determining the 2-dimensioal shape of morphing structures by monitoring simultaneously the bending and twist deflections. The proposed development is based on the non-linear theory of finite elements to extract the transverse linear and angular deflections of a plate-like structure.

The sensors outputs are wirelessly transmitted to the command unit to simultaneously compute maps of the linear and angular deflections and maps of the strain distribution of the entire structure. The deflection and shape information are

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Report Title

Wireless and Distributed Sensing of
Shape and Health Monitoring of Morphing Structures

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This paper presents the development of the theoretical basis for the design of sensor networks for determining the 2-dimensioal shape of morphing structures by monitoring simultaneously the bending and twist deflections. The proposed development is based on the non-linear theory of finite elements to extract the transverse linear and angular deflections of a plate-like structure.

The sensors outputs are wirelessly transmitted to the command unit to simultaneously compute maps of the linear and angular deflections and maps of the strain distribution of the entire structure. The deflection and shape information are required to ascertain that the structure is properly deployed and that its surfaces are operating wrinkle-free. The strain map ensures that the structure is not loaded excessively to adversely affect its service life.

The developed theoretical model is validated experimentally using a prototype of a variable cambered span morphing structure provided with a network of distributed sensors. The structure/sensor network system is tested under various static conditions to determine the response characteristics of the proposed sensor network as compared to other conventional sensor systems.

The presented theoretical and experimental techniques can have a great impact on the safe deployment and effective operation of a wide variety of morphing and inflatable structures such as morphing aircraft, solar sails, inflatable wings, and large antennas.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Number of Papers published in peer-reviewed journals: 0.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

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Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 1

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Graduate Students

NAME	PERCENT_SUPPORTED
Robin Zimmerman	0.33
Daniel Chin	0.33
FTE Equivalent:	**0.66**
Total Number:	**2**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

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FINAL REPORT

Entitled:

Wireless and Distributed Sensing of Shape and Health Monitoring of Morphing Structures

SHORT TERM INNOVATIVE RESEARCH (STIR) PROGRAM.

Proposal # 49637-EG-II

Submitted by:

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Distributed Sensing of the Bending and Twist of Morphing Structures

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Abstract

This paper presents the development of the theoretical basis for the design of sensor networks for determining the 2-dimensioal shape of morphing structures by monitoring simultaneously the bending and twist deflections. The proposed development is based on the non-linear theory of finite elements to extract the transverse linear and angular deflections of a plate-like structure.

The sensors outputs are wirelessly transmitted to the command unit to simultaneously compute maps of the linear and angular deflections and maps of the strain distribution of the entire structure. The deflection and shape information are required to ascertain that the structure is properly deployed and that its surfaces are operating wrinkle-free. The strain map ensures that the structure is not loaded excessively to adversely affect its service life.

The developed theoretical model is validated experimentally using a prototype of a variable cambered span morphing structure provided with a network of distributed sensors. The structure/sensor network system is tested under various static conditions to determine the response characteristics of the proposed sensor network as compared to other conventional sensor systems.

The presented theoretical and experimental techniques can have a great impact on the safe deployment and effective operation of a wide variety of morphing and inflatable structures such as morphing aircraft, solar sails, inflatable wings, and large antennas.

Keywords: Morphing structures, distributed sensing, shape monitoring, bending and twist deflections

1. Introduction

Extensive efforts have been exerted recently to develop a wide variety of morphing wing aircraft because of their attractive attributes. These aircraft can perform drastically different mission roles during a single flight such as loitering and strike roles in a manner mimicking the efficient flight of birds and other flying creatures. In such roles, the aircraft wing can change from a high span/large surface area for a loitering wing to a low span/low area for a strike wing. The ability of the aircraft to morph enables the control of critical performance characteristics, such as the turning radius, endurance, payload, and maximum velocity. Furthermore, morphing aircrafts have unique maneuvering capabilities which can be achieved by pulling one wing in and rolling the other one. Hence, considerable weight can be saved by eliminating the usual control surfaces.

The concept of the ability to optimize the wing shapes for a particular flight regime is an appealing concept that has already been considered for several wings such as the AFTI/F-111 Mission Adaptive Wing (MAW) with its variable camber wing (Cesnik *et al.,* 2004) and NASA's hyper-elliptic cambered span (HECS) wing (Davidson *et al*., 2003; Manzo *et al*., 2005). Morphing wings have also come in many different designs such as a variable span morphing wing (Bae *et al*. 2005), folding wings, and sliding skin wings (Lee *et al*. 2005).

Designs for morphing wings also include polyhedral wing shapes which allow for variations between dihedral and anhedral wing sections. Refinement of these sections lead to near continuous morphing cambered span wing shapes (Wiggins *et al*., 2004). These designs focus on vertical deflection rather than horizontal orientation. Wings retain general dimensions, but introduce gradual bends to optimize aerodynamics for the desired flight.

Accordingly, proper monitoring of the shape of the morphing wings is essential to ensuring their continued effective performance. The monitored shape information can then be fedback to appropriate shape control systems to achieve the desired shape while ensuring that the surfaces are aerodynamically smooth and wrinkle-free. Furthermore, the deflections due to aerodynamic loads can also be compensated for any flying condition.

Several attempts have already been made to monitor the shape and health of morphing structures using fiber optic sensors (McGowan *et al*. 2003**,** Wood *et al*. 2000a, b, Wlezien *et al*. 1998). However, these attempts are still in their preliminary stages and the fiber optics sensing systems used are expensive, rigid, and unsuitable for monitoring large shape changes without being susceptible to failure or performance degradation. Akl *et al*. (2007) developed a radically different class of distributed sensors that does not suffer from the serious limitations of current sensor systems. The sensor consists of a specially configured distributed network of wire sensors that are embedded in the composite fabric of the morphing structures. The sensors outputs are wirelessly transmitted to the command unit to simultaneously compute maps of the linear and angular deflections, i.e. the shape, and maps of the strain distributions. The feasibility of this class of sensors has been demonstrated for in-plane two-dimensional morphing by Akl *et al*., (2007) and Smoker and Baz (2007).

In this paper, the studies of Akl *et al*., (2007) and Smoker and Baz (2007) are extended to three-dimensional morphing motions whereby in-plane and out-of-plane motions are monitored simultaneously. With such capabilities, the proposed sensor network can present a viable means for monitoring realistic morphing wings. Furthermore, integration of the sensor network with the supporting electronics and with arrays of flexible actuators will enable the development of autonomously operating new generation of morphing and inflatable structures.

Accordingly, this paper is organized in five sections. In section 1, a brief introduction has been presented. In section 2, the mathematical basis of the three-dimensional sensor network is developed. Section 3 summarizes the experimental work, the development of a prototype morphing structure and its performance characteristics. Section 4, presents a comparison between the experimental and theoretical predictions along with comparisons with the predictions obtained by the commercial finite element package ANSYS. A summary of the paper and the conclusions reached are given in Section 5.

2. Mathematical Model

2.1. Overview

The development of the distributed sensor for monitoring the large deformation of morphing structures will be based on the work of Akl *et al*. (2007) which employed networks of distributed wire sensors to monitor small amplitudes of vibration of beams and plates. For small deflections, the sensor relies in its operation on the linear theory of finite elements to extract the transverse linear and angular deflections. But for large deflections, the proposed sensor network will be based on the non-linear theory of finite elements to extract the transverse linear and angular deflections as well as the in-plane longitudinal deflections.

2.2. Theory

The distributed sensor proposed here extends the one-dimensional idealization of the beam which was presented in section ***2.2*** to a two-dimensional representation of the morphing plate-like structure shown in Figure (1).

The figure shows a cross section of the plate-like morphing structure in the *x*-*y* plane indicating the arrangement of a single wire oriented along the *x*-axis. Similar arrangements are done for wires oriented parallel to the *y*-axis. All the wires are divided into several segments that allow the continuous monitoring of the linear, angular and twist angle of several discrete points distributed over the surface of the morphing structure. Such monitoring is achieved by measuring and processing changes in the lengths of the different segments of the wire sensor in a manner similar to that described in section ***2.2***. The processing of the length changes is governed by the theory of non-linear finite element to extract the nodal deflections.   A brief description of the proposed theory is described below**.**

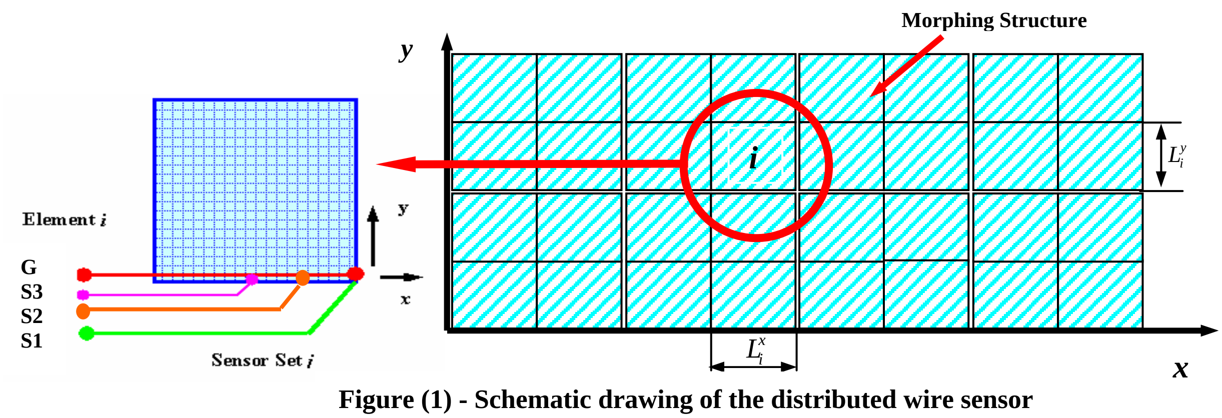


Figure (1) - Schematic drawing of the distributed wire sensor

The von Karman strains ε_x and ε_y, in the *x* and *y* directions, in a wire sensor network placed at a distance ***a*** from the neutral plane are given by:

$$\varepsilon_x = u_{,x} + \frac{1}{2}\left(w_{,x}\right)^2 - a w_{,xx} \qquad \text{and} \qquad \varepsilon_y = u_{,y} + \frac{1}{2}\left(w_{,y}\right)^2 - a w_{,yy} \tag{1}$$

The in-plane and out-of-plane deflections (*u, v*, and *w*) can be approximated as follows:

$$u = \{N_u\}\{\Delta\}, \quad v = \{N_v\}\{\Delta\}, \quad \text{and} \quad w = \{N_w\}\{\Delta\} \tag{2}$$

where $\{N_u\}$, $\{N_v\}$ and $\{N_w\}$ are appropriate shape functions for in-plane and out-of-plane displacements, and $\{\Delta\}$ is the nodal deflection vector defined as

$$\{\Delta\} = \{u \quad v \quad w \quad w_{,x} \quad w_{,y}\}^T \tag{3}$$

Accordingly, the changes in the length of a wire segments *j* and *k* in the *x* and *y* directions will be given by:

$$\Delta L_{i\,j}^{x} = \int_0^{L_{i\,j}^{x}} \varepsilon_x dx \qquad \text{and} \qquad \Delta L_{i\,k}^{y} = \int_0^{L_{i\,k}^{y}} \varepsilon_y dy \tag{4}$$

where $j=1,2,..,J$ and $k=1,2,..,K$ with *J* and *K* denoting the total number of wire segments in the *x* and *y* directions inside the i^{th} element.

Substituting equations (1) into equation (2) yields

$$\varepsilon_x = \left\{N_{u_{,x}}\right\}\{\Delta\} + \frac{1}{2}\{\Delta\}^T\left\{N_{w_{,x}}\right\}^T\left\{N_{w_{,x}}\right\}\{\Delta\} - a\left\{N_{w_{,xx}}\right\}\{\Delta\},$$

and

$$\varepsilon_y = \left\{N_{v_{,y}}\right\}\{\Delta\} + \frac{1}{2}\{\Delta\}^T\left\{N_{w_{,y}}\right\}^T\left\{N_{w_{,y}}\right\}\{\Delta\} - a\left\{N_{w_{,yy}}\right\}\{\Delta\}. \tag{5}$$

The changes $\Delta L_{i\,j}^{x}$ and $\Delta L_{i\,k}^{y}$ in the length of a wire segments *j* and *k* in the *x* and *y* directions can be determined from substituting equation (4) into equation (5) to give

$$\Delta L_{ij}^{x} = \int_{0}^{L_{ij}} \left(\left\{ N_{u_{,x}} \right\} + \frac{1}{2} \{\Delta\}^{T} \left\{ N_{w_{,x}} \right\}^{T} \left\{ N_{w_{,x}} \right\} - a \left\{ N_{w_{,xx}} \right\} \right) dx \cdot \{\Delta\},$$

and
$$\Delta L_{ik}^{y} = \int_{0}^{L_{ik}} \left(\left\{ N_{v_{,y}} \right\} + \frac{1}{2} \{\Delta\}^{T} \left\{ N_{w_{,y}} \right\}^{T} \left\{ N_{w_{,y}} \right\} - a \left\{ N_{w_{,yy}} \right\} \right) dy \cdot \{\Delta\}. \tag{6}$$

which can be expressed as:

$$\Delta L_{ij}^{x} = \left(\{g_{1_{ij}}\} + \{\Delta\}^{T} [g_{2_{ij}}] + \{g_{3_{ij}}\} \right) \{\Delta\},$$

and
$$\Delta L_{ik}^{y} = \left(\{h_{1_{ik}}\} + \{\Delta\}^{T} [h_{2_{ik}}] + \{h_{3_{ik}}\} \right) \{\Delta\}. \tag{7}$$

for *j=1,2,..,J* and *k=1,2,.. ,K.*

In equation (7),

$$\{g_{1_{ij}}\} = \int_{0}^{L_{ij}} \left\{ N_{u_{,x}} \right\} dx,\ [g_{2_{ij}}] = \frac{1}{2} \int_{0}^{L_{ij}} \left\{ N_{w_{,x}} \right\}^{T} \left\{ N_{w_{,xx}} \right\} dx, \text{ and } \{g_{3_{ij}}\} = -a \int_{0}^{L_{ij}} \left\{ N_{w_{,xx}} \right\} dx\,,$$

and
$$\{h_{1_{ik}}\} = \int_{0}^{L_{ik}} \left\{ N_{v_{,y}} \right\} dy,\ [h_{2_{ik}}] = \frac{1}{2} \int_{0}^{L_{ik}} \left\{ N_{w_{,y}} \right\}^{T} \left\{ N_{w_{,y}} \right\} dy, \quad \text{and} \quad \{h_{3_{ij}}\} = -a \int_{0}^{L_{ij}} \left\{ N_{w_{,yy}} \right\} dy \tag{8}$$

Hence, assembly of all the length changes, in the i^{th} element, gives:

$$\{\Delta L_i\} = \left(\begin{bmatrix} \{g_{1_1}\} \\ \cdots \\ \{g_{1_J}\} \\ \\ \{h_{1_1}\} \\ \cdots \\ \{h_{1_K}\} \end{bmatrix} + \begin{bmatrix} \{\Delta_i\}^{T} [g_{2_1}] \\ \cdots \\ \{\Delta_i\}^{T} [g_{2_J}] \\ \\ \{\Delta_i\}^{T} [h_{2_1}] \\ \cdots \\ \{\Delta_i\}^{T} [h_{2_K}] \end{bmatrix} + \begin{bmatrix} \{g_{3_1}\} \\ \cdots \\ \{g_{3_J}\} \\ \\ \{h_{3_1}\} \\ \cdots \\ \{h_{3_K}\} \end{bmatrix} \right) \{\Delta_i\} \tag{9}$$

For the entire morphing structure, equation (9) becomes:

$$\{\Delta L\} = \left([G_1] + [G_2(\{\Delta\})] + [G_3]\right)\{\Delta\} = [G]\{\Delta\} \tag{10}$$

where $\{\Delta L\} = \{\Delta L_1 \; ... \; \Delta L_N\}^T$. Note that the matrix equation (10) represents a set of $\boldsymbol{N}$ equations in the $\boldsymbol{N}$ unknown degrees of freedom of the vector $\{\Delta\}$. The elements of the vector $\{\Delta\}$ can be computed by inverting the matrix $[G]$. However, such a computational process is iterative in nature as matrix $[G_2]$ is a function of the unknown deflection vector $\{\Delta\}$. The iterative solution of equation (9) is given by

$$\{\Delta\}_n = \left([G_1] + [G_2(\{\Delta\}_{n-1}) + [G_3]\right)^{-1} \; \{\Delta L\} \tag{11}$$

where n is the n^{th} iteration, and $\{\Delta\}_0$ is the initial guess for the deflection vector given by

$$\{\Delta\}_0 = \left([G_1] + [G_3]\right)^{-1} \{\Delta L\} \tag{12}$$

It is important here to note that the proposed distributed wire sensor is in effect a **distributed strain gage sensor**. Such a distributed nature of the sensor has many inherent advantages. The most important is its ***interpolating capabilities*** as can be ascertained from equation (2). Hence, once the nodal deflection vector $\{\Delta\}$ is computed, the deflections $\boldsymbol{u}$**,** $\boldsymbol{v}$ and $\boldsymbol{w}$ at any location (x, y) can be easily determined using the interpolating functions $[N_u]$, $[N_v]$, and $[N_w]$ as given by equation (2). Also, the angular deflection $w_{,x}$ and the twist angle $w_{,y}$, at any location (x, y) can be extracted from the nodal deflection vector $\{\Delta\}$ as implied by equation (3).

Similarly, maps of the strain field over the entire morphing structure can then be determined using equation (5). Such interpolation capabilities of the distributed wire sensor render it suitable for monitoring the entire deflection and strain fields for large structures with only a small number of wire segments.

3- Experimental Morphing Structure

3.1. Prototype of Morphing Structure

A prototype of the morphing structure is built from an acrylic plate (0.3 x 0.6 m x 0.003125m) as shown in Figure (2). The plate is mounted in a cantilevered fashion from one end and is connected to four shape memory spring actuators at its other end (Figure 2a). Proper activation of the four actuators can subject the morphing plate to pure bending, pure twist, or combination of bending and twist. A network of the distributed wire sensor is deposited on the plate according to the configuration shown in Figure (2b). This configuration consists of a total of ten sensor segments in order to extract the deflection vectors of the free ends (***A*** and ***B***) of the morphing structure. Each end has five degrees of freedom (u, v, w, $w_{,x}$, and $w_{,y}$). Hence, changes in the length of the tens sensor segments can be used to calculate the ten degrees of freedom (u_A, v_A, w_A, $w_{A,x}$, $w_{A,y}$, u_B, v_B, w_B, $w_{B,x}$, and $w_{B,y}$) and accordingly generate maps of the deflection and strain fields over the entire surface of the morphing plate.

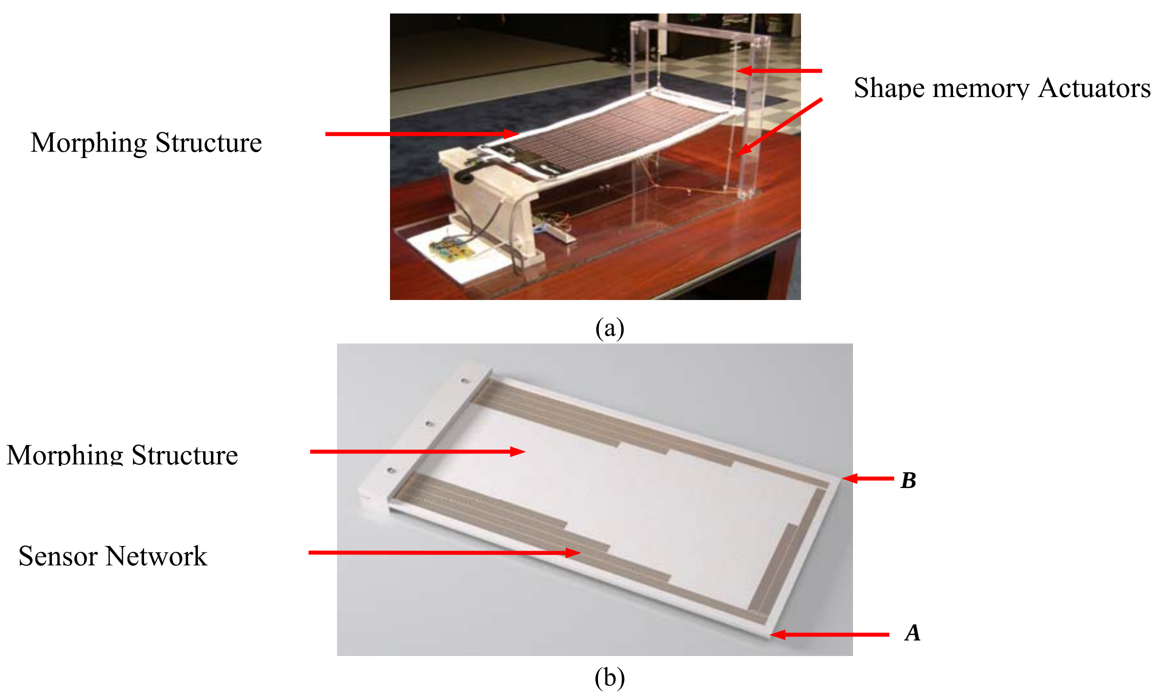


Figure (2) – Photograph of the morphing plate (a) and arrangement of the distributed sensor network

3.2. Electronic Circuitry of the Distributed Sensor

The electronic circuitry can be broken down into five sections. These sections are: the power supply, the micro-controller, the amplifiers, Wheatstone bridges, and the transceiver. Interaction between the five sections is according to the block diagram shown in Figure (3).

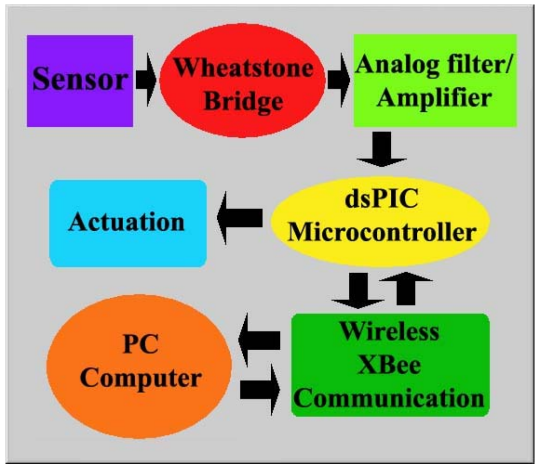


Figure (3) – Block diagram of the electronic circuitry of the distributed sensor system

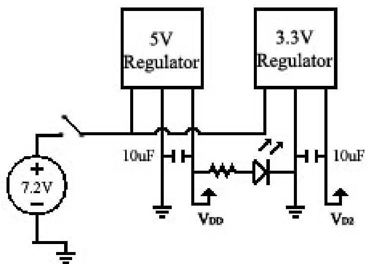
The power supply circuit is powered by a 7.2V Lithium-Ion Battery. As shown from Figure (4a), the battery output is fed through a low drop out 5V voltage regulator for the micro-controller, amplifier and Wheatstone bridge power supply as well as a 3.3V low drop out regulator for the wireless transceiver.

The micro-controller for the circuit is a dsPIC30F6011A as shown in Figure (4b). The dsPIC30F6011A is set up to run at 29.48 Mhz on an internal oscillator. The microchip's 16 analog inputs are connected to amplifier outputs through a low-pass RC filter. The microchip's primary Universal Asynchronous Receiver Transmitter (UART) pins are connected to the wireless transceiver to communicate the host computer. Programming for the microcontroller is made possible through its In Circuit Serial Programming (ISCP) pins.

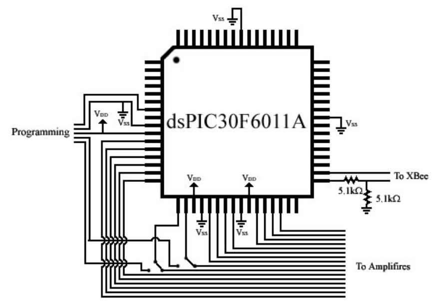
The amplifier used is a dual amplifier INA2126 shown in Figure (4c). Eight of these amplifiers are connected to 16 Wheatstone bridges and relay the amplified signal back to the dsPIC30F6011A microcontroller through a low-pass RC filter. The amplifier is tuned to a gain of 992.6 with a 5.1kOhm resistor.

The Wheatstone bridge is a simple quarter bridge circuit that uses 350 Ohm resistors with a 500Ohm potentiometer for tuning as shown in Figure (4d).

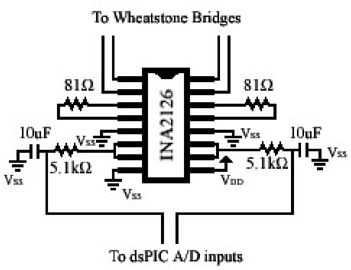
The outputs of the amplified Wheatstone bridge signal are forwarded to the host computer through an XBee transceiver shown in Figure (4e). Data is transferred at a baud speed of 9600bps. A voltage divider is included to account for the difference in power levels between the micro-controller and transceiver. An LED is also connected to the transceiver to show that it is active. Figure (5) shows a photograph of the entire circuit.



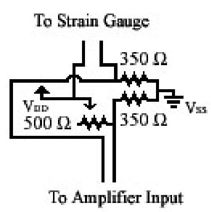
(a) - Power Supply Circuit



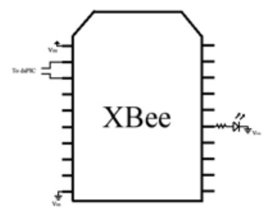
(b) - Micro-Controller Circuit



(c) - Amplifier Circuit



(d) - Wheatstone Quarter Bridge



(e) - Transceiver

Figure (4) – Main components of the electronic circuitry of the sensor system

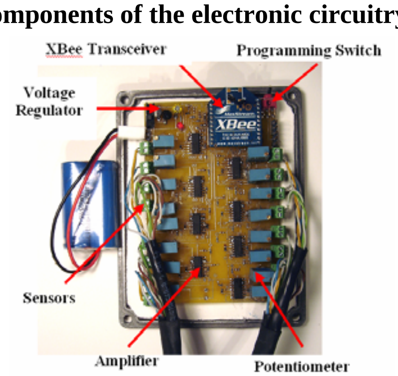


Figure (5) – Photograph of the electronics system of the distributed sensor

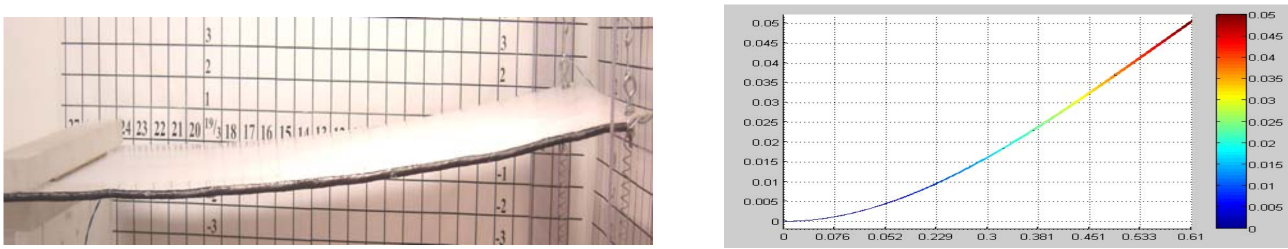
3.3. Performance of the Distributed Sensor

The effectiveness of the sensor in monitoring the bending and twist of a morphing structure is determined for four morphing strategies. These strategies include: pure upward bending, pure downward bending, pure twist, and combined twist and bending.

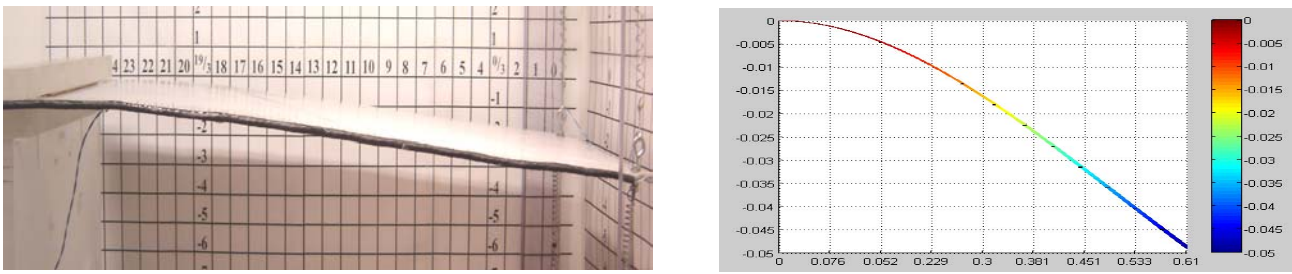
Figure (6) shows a comparison between the actual shape of the morphing plate and the shape measured by the distributed sensor network for the four morphing strategies.

Figure (6) shows a close qualitative agreement between the actual and the measured shapes. In Section 4, a quantitative comparison is presented between the actual and measured shapes as well as with predictions from a commercial finite element package (ANSYS).

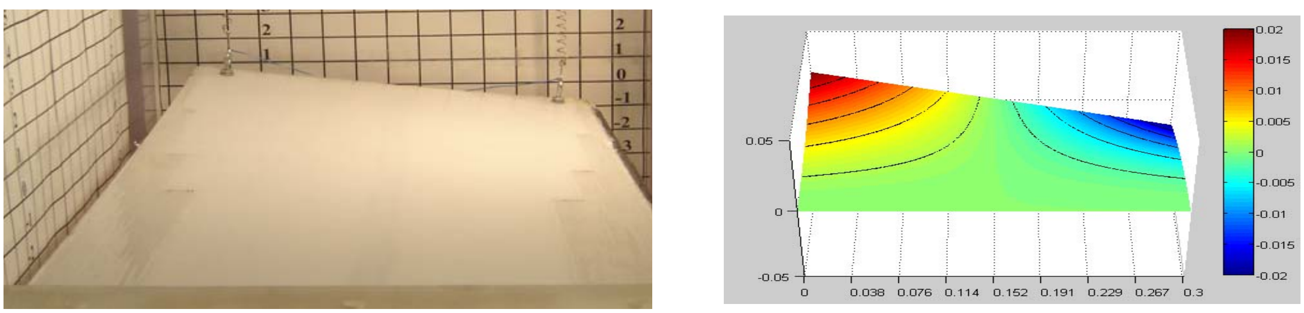
Actual shape **Measured shape**



(a) - pure upward bending



(b) – pure downward bending



(c) – pure twist

(d) –combined twist and bending

Figure (6) - Comparisons between the actual and measured shapes of the morphing plate for different morphing strategies.

4 – Comparisons Between Theory and Experiments

4.1. Finite Element Model

A finite element model is developed using ANSYS software package. The model uses the solid shell element 190 and the morphing plate is divided into 675 elements as shown in Figure (7). The predictions of the finite element model are shown in Figure (8) for the four morphing strategies along with the shapes measured by the distributed sensor network.

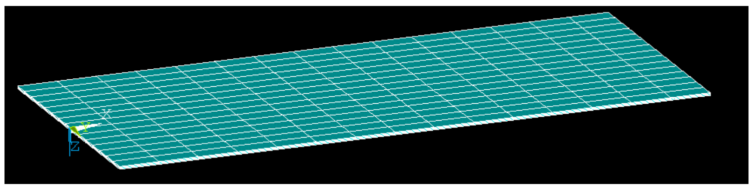
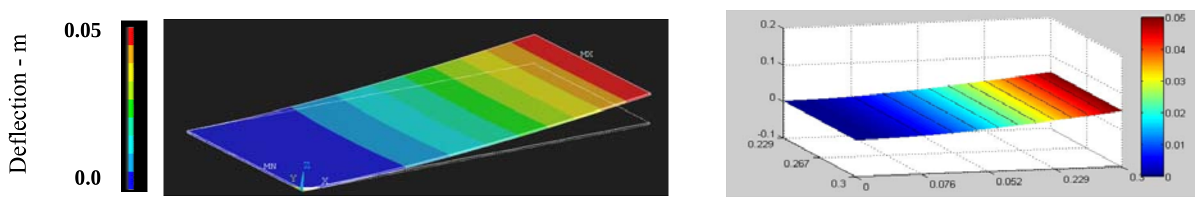
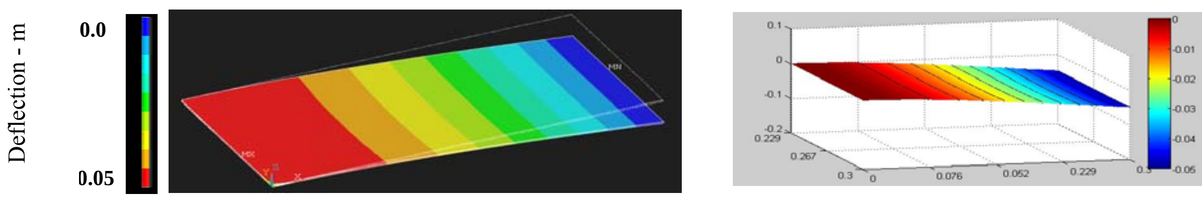


Figure (7) – Finite element model of the morphing plate

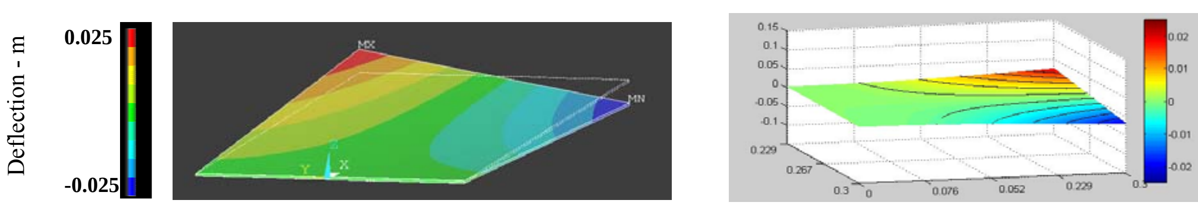
ANSYS **Distributed Sensor Measurements**



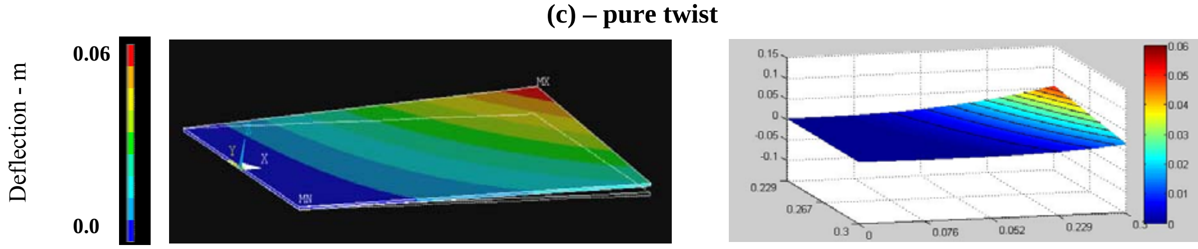
(a) – pure upward bending



(b) – pure downward bending



(c) – pure twist

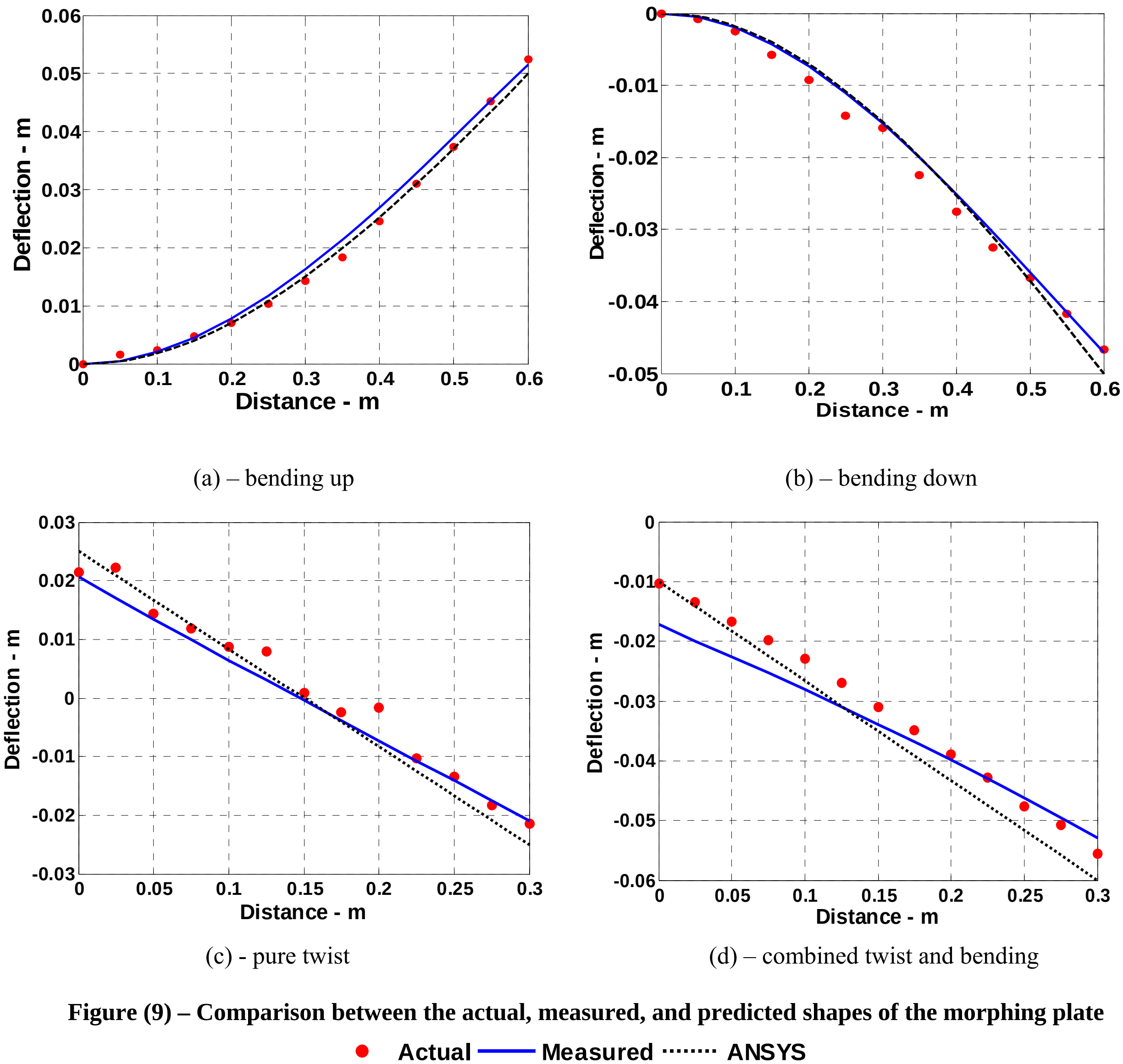


(d) – combined bending and twist

Figure (8) – Comparison between the measured and predicted shapes of the morphing plate

The displayed results suggest close agreement between the predictions of the ANSYS finite element model and the shapes measured by the distributed sensor network.

Figure (9) presents comprehensive comparisons between the actual, the measured, and predicted shapes of the morphing structures for the considered four morphing strategies.



(a) – bending up

(b) – bending down

(c) - pure twist

(d) – combined twist and bending

Figure (9) – Comparison between the actual, measured, and predicted shapes of the morphing plate

The displayed results confirms the close agreement between the experimental results and the theoretical predictions of the shape of the morphing plate as it is subjected to pure bending, pure twist, and combined bending and twist.

5. Conclusions

This paper has presented a demonstration of the usage of distributed sensors for the purpose of monitoring the bending and twist of a morphing structure. The unique ability of this sensor to estimate the shape of the structure when subjected to a combined state of bending and twist suggests its potential for application to shape monitoring of morphing wings. Ultimately, integration of the sensor network with the supporting electronics and arrays of flexible actuators will enable the development of autonomously operating new generation of morphing and inflatable structures.

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NOMENCLATURE

a	distance from neutral plane
g and h	vectors resulting from integrating shape functions
J	number of wire segments in the x direction
K	number of wire segments in the y direction
$\{N_{u,v,w}\}$	shape functions for u, v, w respectively
u	in-plane displacement in the x direction
v	in-plane displacement in the y direction
w	transverse deflection
x, y	coordinate system
$\{\Delta\}$	nodal deflection vector
$\{\Delta\}_i$	nodal deflection vector after the i^{th} iteration
$\{\Delta L\}$	vector of length changes
$\varepsilon_x, \varepsilon_y$	strains in the x and y directions